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Coupled computations of three-dimensional shape and material

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Retinal image structure arises from the interaction between a surface's three-dimensional shape, its reflectance and transmittance properties, and the surrounding light field. Any local image structure can be generated by an infinite number of different combinations of surface properties, which suggests that the visual system must somehow constrain the possible scene interpretations. The research on this has searched for such constraints in statistical regularities of two-dimensional image structure [1,2]. Here, we present a new class of displays in which the perception of material properties cannot be explained with two-dimensional image properties. The displays manipulate the perceived three-dimensional shape of identical luminance gratings, and demonstrate that perceived three-dimensional shape can alter perceived surface reflectance.

The material properties of a surface physically constrain the rate that luminance varies with its three-dimensional surface orientation. For simplicity, we restrict attention to singly-curved surfaces, which project luminance gradients that only vary along the direction of the surface curves. The steepness of the luminance gradients depends on the surface's three-dimensional shape, surrounding light field, and reflectance function. The left side of Figure 1A depicts a matte (Lambertian) surface that projects a luminance gradient that varies as a cosine of the angle between the surface normal and the direction of the incident illumination. The steepness of luminance gradients generated by a specular surface depends on a surface roughness parameter, which modulates the 'spread' of the specular lobe. For a fixed surface geometry and moderate amounts of surface roughness, specular surfaces will typically generate steeper luminance gradients than Lambertian surfaces (Figure 1A).

Thus, for a fixed surface geometry, the rate that luminance varies as a function of local three-dimensional surface orientation could potentially provide information about a surface's material properties. However, identical luminance gradients can sometimes be generated by surfaces with different reflectance functions if three-dimensional shape and the light field are chosen appropriately. For example, a matte surface can generate the same gradient as the specular surface in Figure 1A if its three-dimensional surface orientation varies more rapidly than the specular surface. If the visual system exploits constraints imposed by three-dimensional shape to derive material properties, then it should be possible for an identical luminance gradient to appear as either a matte or specular material by simply changing the perceived three-dimensional shape. Previous work has suggested that specular reflectance can be derived directly from the two-dimensional images, which implies that the perception of specularity could be derived prior to any explicit representation of three-dimensional structure [1–7].

To assess whether the visual system exploits three-dimensional geometric constraints to derive material properties, we exploited previous work which showed that perceived three-dimensional shape [8–10] and illumination direction [8,10] can be altered by manipulating the shape of bounding contours. Figure 1B depicts a pair of identical luminance gratings. The only physical difference between the left and right images is the shape of the bounding contours that flank the grating along its left and right sides. The shape information provided by the contours transforms the perceived three-dimensional shape and the illumination direction of the two surfaces, as has been shown previously [8–10]. Note, however, that there is also a clear change in perceived material properties of the two surfaces: the left image appears matte, whereas the right image appears metallic.

To experimentally document these percepts, observers selected the surface that appeared more metallic from a pair of images. We tested all possible combinations of the two three-dimensional shapes with six different luminance gradients parametrically varying in steepness (see Figure S1 in the Supplemental Information). Figure 1B plots the proportion of times that each three-dimensional shape appeared more specular than the comparison

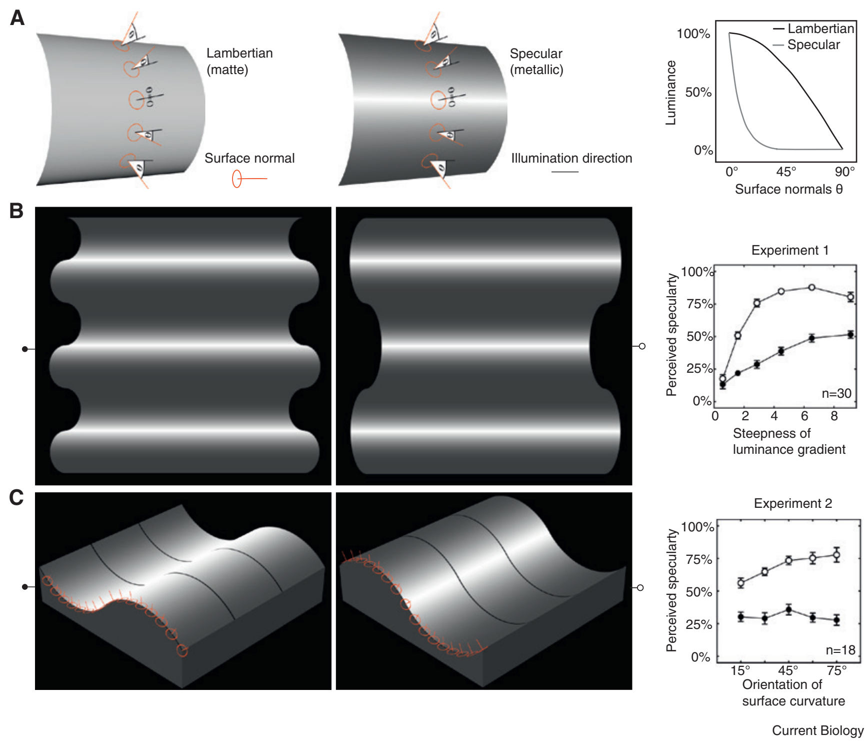

Figure 1. Material perception depends on perceived three-dimensional shape.
(A) Material properties are derivable from the rate that luminance varies with surface orientation, which is low for Lambertian materials and high for specular materials. The luminance gradients in the left image of (B) and (C) are identical to the gradients directly across from them in the right image. The only difference between the left and right images is the shape of the contours, which induces different percepts of three-dimensional shape. The left images appear as matte surfaces, whereas the right images appear metallic, consistent with the apparent rate of change in surface orientation across the luminance gradients. The proportion of trials that observers perceived each image to be more metallic than comparison stimuli is plotted in the graphs directly to the right of each pair of example stimuli (see Supplemental Information for the full parametric variation of the stimuli depicted). Error bars show standard errors of the mean of all observers.

stimuli as a function of the steepness of the gradient. The data confirm that identical luminance gradients appear more specular when they have the three-dimensional shape in the right of Figure 1B than the left, and that steep gradients elicit the strongest effects of three-dimensional shape. Ratings data produced the same results (see Supplemental Information).

Experiment 2 tested whether these results depend on differences in the range of surface normals or because the luminance maxima of the highlights of the matte surface fell on improbable locations for specular reflections (curvature inflection points). Identical luminance gradients were generated such that the 'highlight' was centred on an inflection point, but the range of surface normals in the neighbourhood of the highlight was smaller for the right image (which appears metallic) than the left image (which appears matte; see Figure 1C) . Experiment 2 confirmed that the difference in perceived material scales with the difference in the range of surface normals (see Supplemental Figure S2 for example stimuli). This experiment provides further evidence that the visual system uses information about the range of three-dimensional surface normals (or relatedly, three-dimensional surface curvature) associated with a luminance gradient to compute material properties.

The results reported here demonstrate that perceived three-dimensional shape can modulate the inferred 'scatter' associated with a surface's reflectance function. It has been previously shown that three-dimensional shape manipulations can modulate the experience of material properties [1,6,7], but these manipulations induced a variety of changes in two-dimensional image properties. It is therefore not possible to determine whether three-dimensional shape representations play any causal role in modulating the perception of material properties in previous studies. Our results demonstrate that the human visual system exploits physical constraints imposed by three-dimensional surface curvature — the range of surface normal — to compute the relative scatter of a surface's reflectance function. Whereas the majority of work has focused on deriving surface and material properties directly from images [1,2], the findings reported here suggest that at least some aspects of the computations underlying material perception are derived from higher order representations in which three-dimensional shape has been made explicit.

Supplemental Information

Supplemental information includes Supplemental Results, Experimental Procedures, and two figures and can be found with this article online at http://dx.doi.org/10.1016/j.cub.2015.01.062.

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